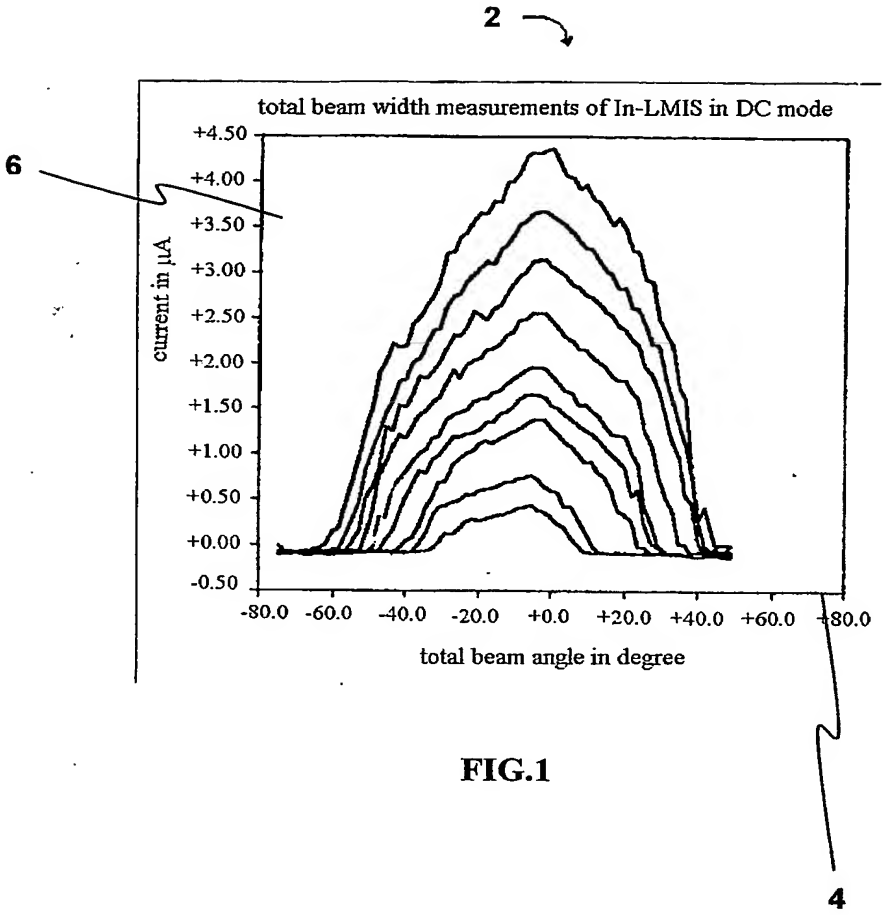
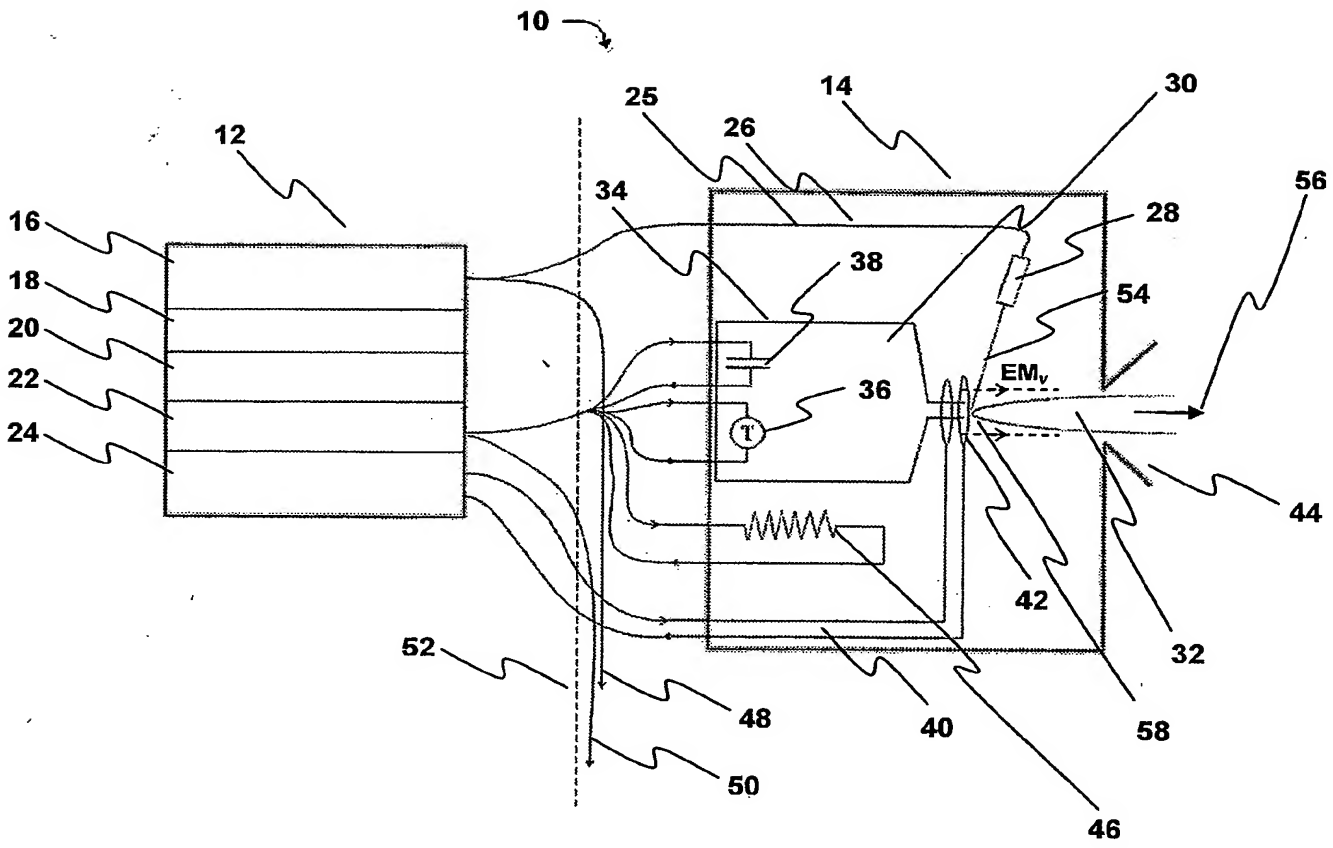


FIG.1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56
58
EMv

FIG. 2

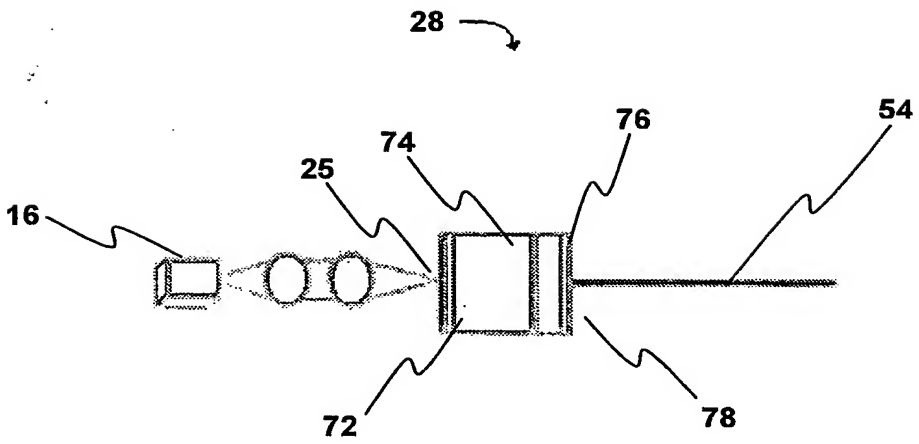

FIG. 3

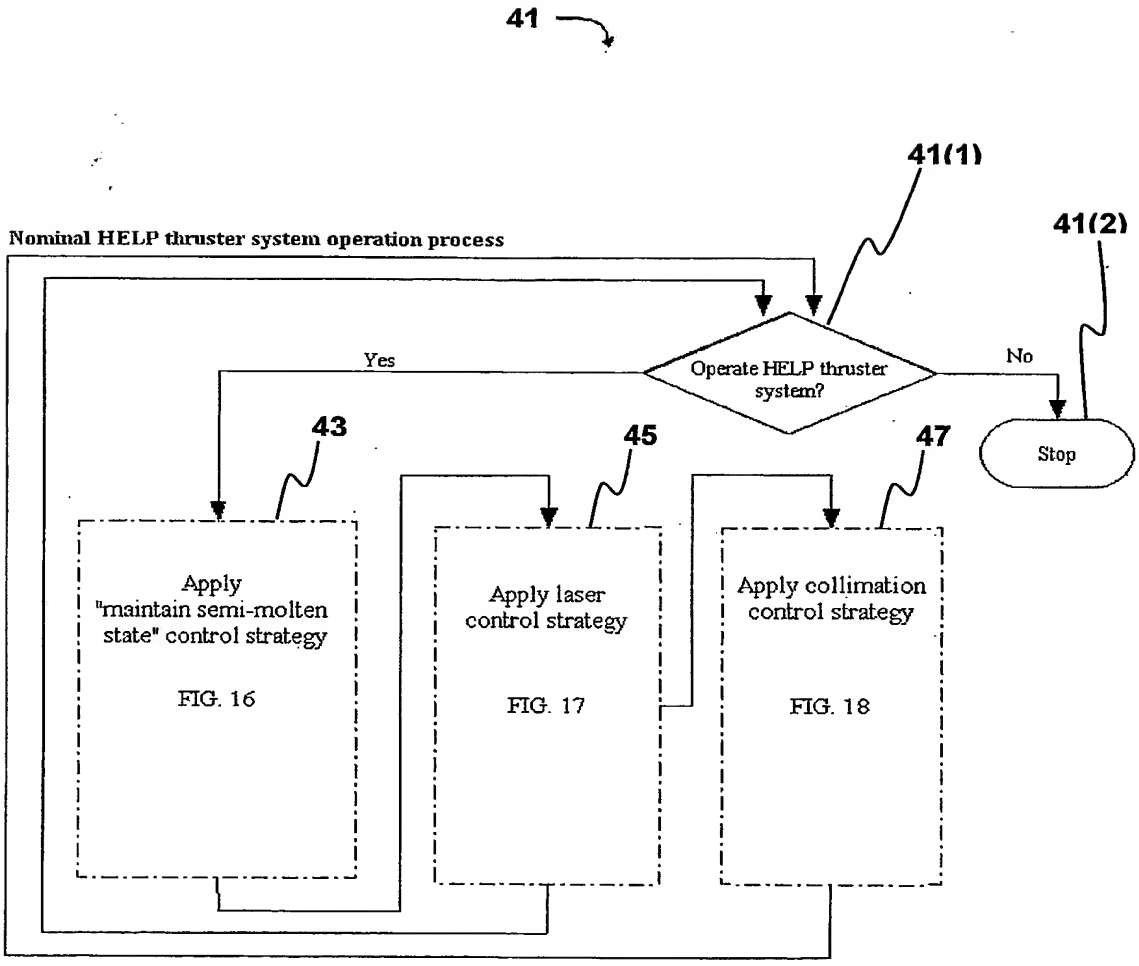
41
41(1)
41(2)
Nominal HELP thruster system operation process
Operate HELP thruster system?
Yes
No
Stop
43
45
47
Apply "maintain semi-molten state" control strategy
FIG. 16
Apply laser control strategy
FIG. 17
Apply collimation control strategy
FIG. 18

FIG. 4

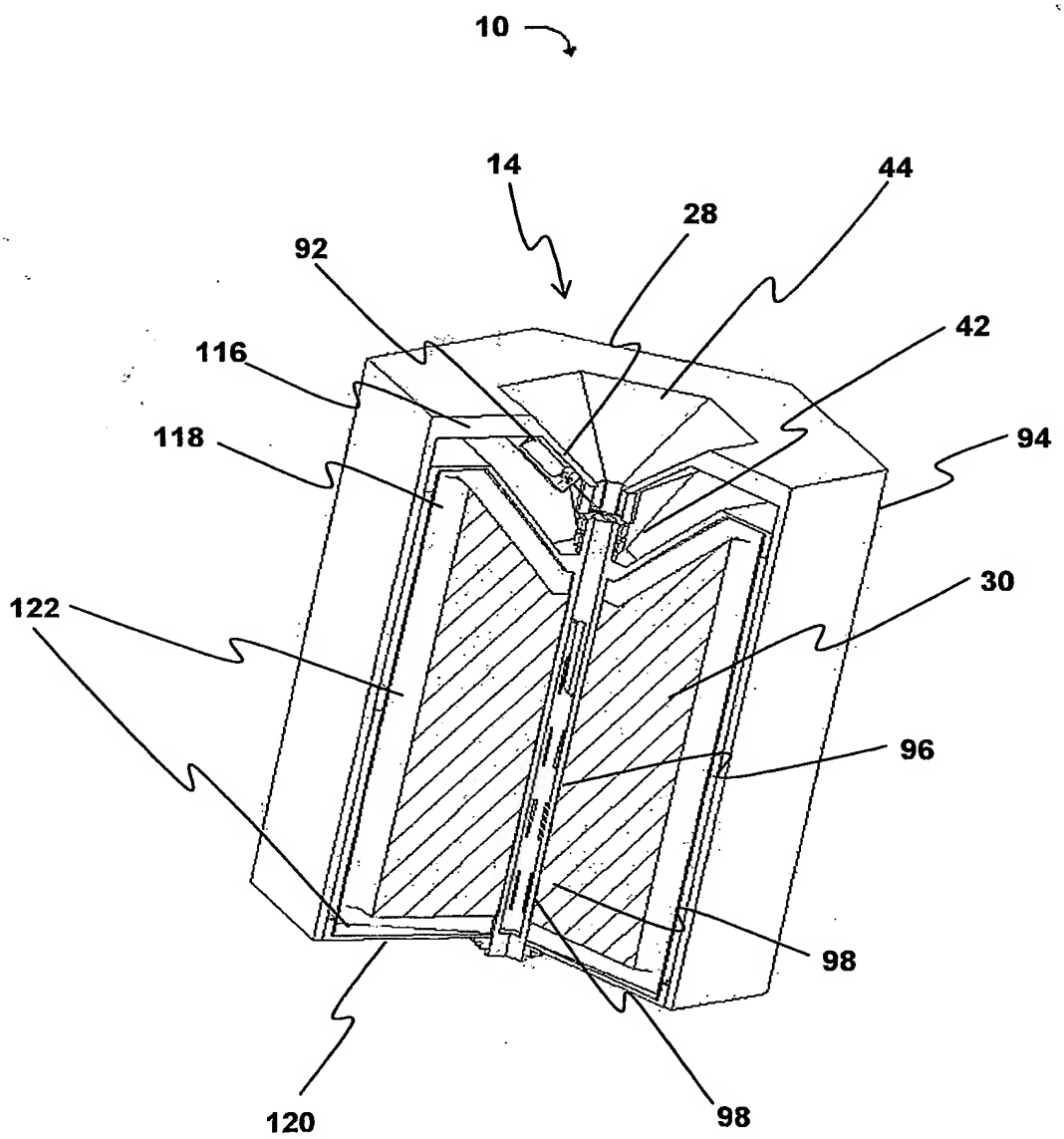

FIG. 5

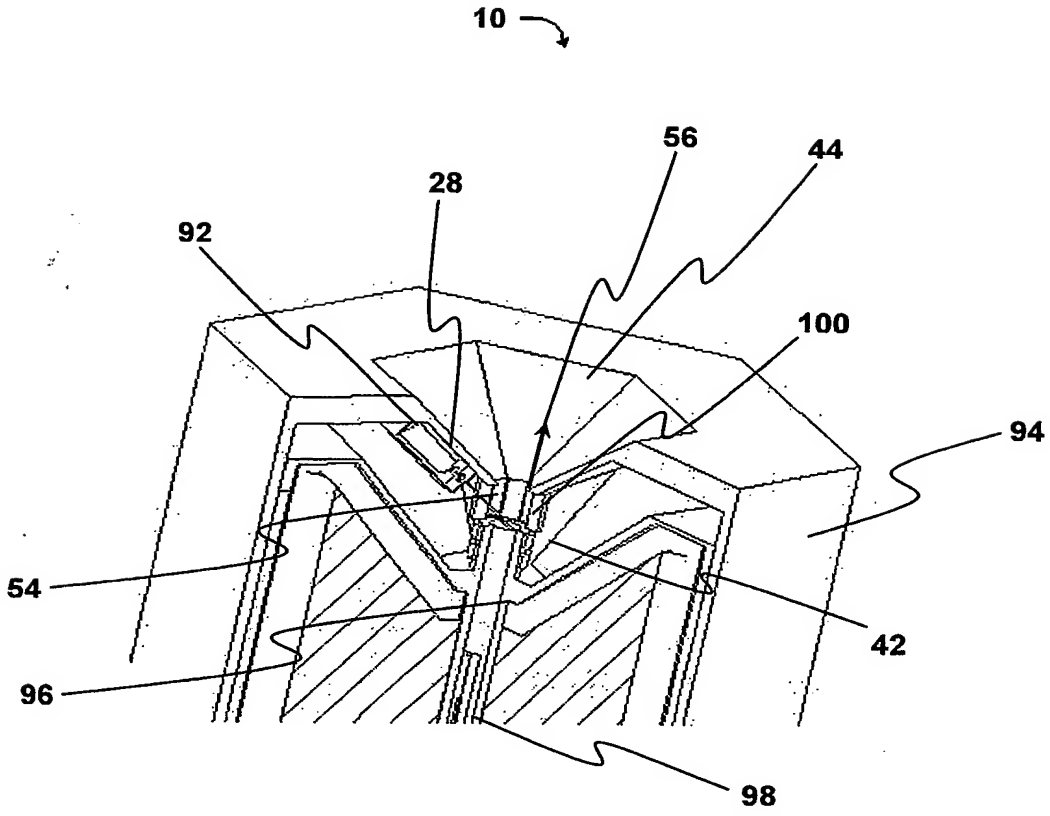

FIG. 6

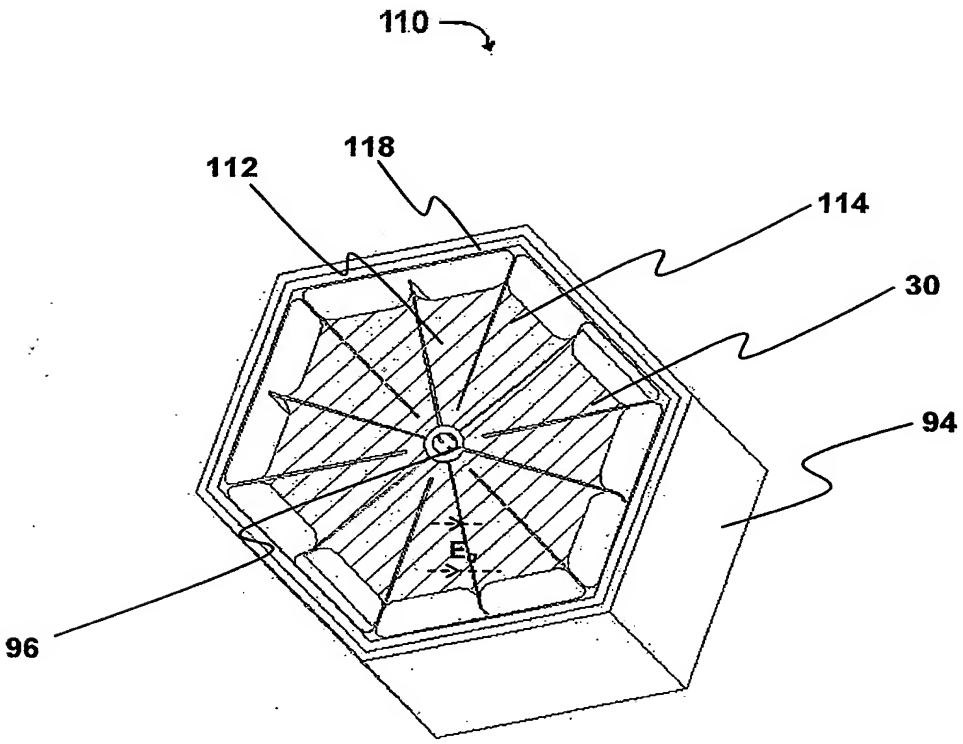

FIG. 7

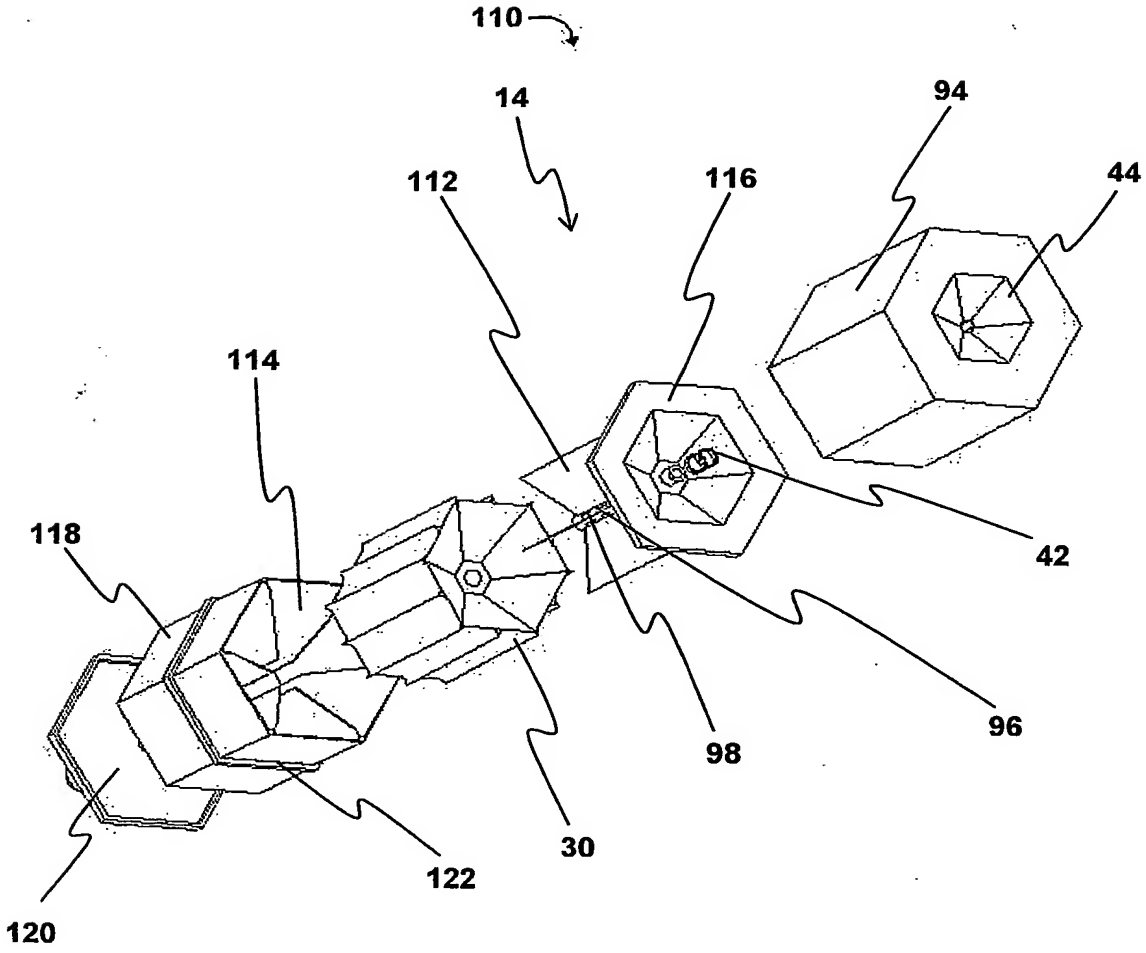

FIG. 8

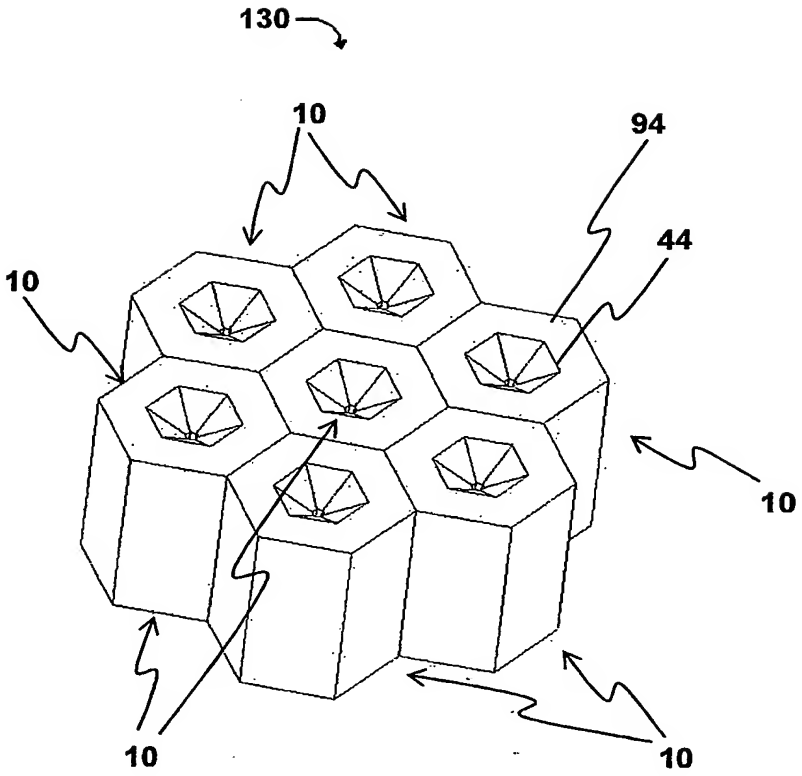

FIG. 9

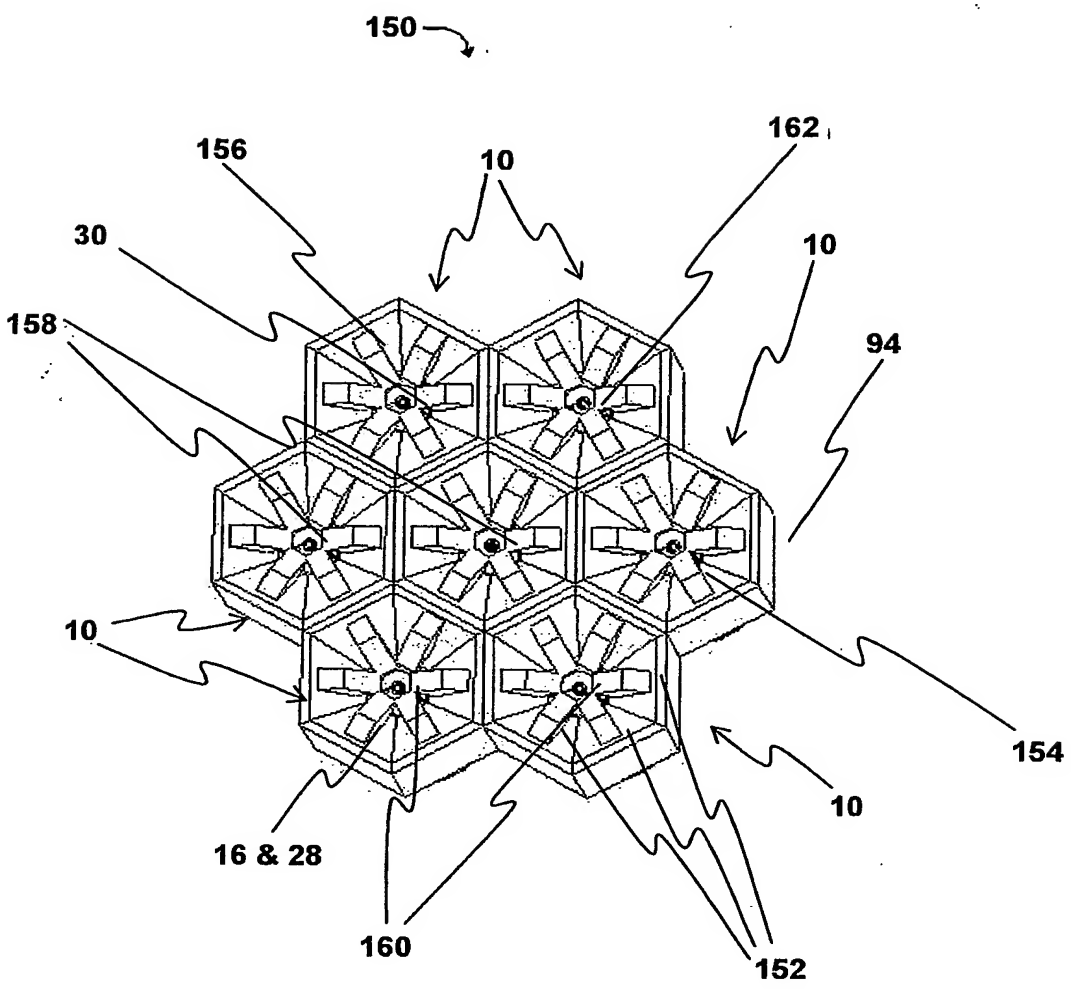

FIG. 10

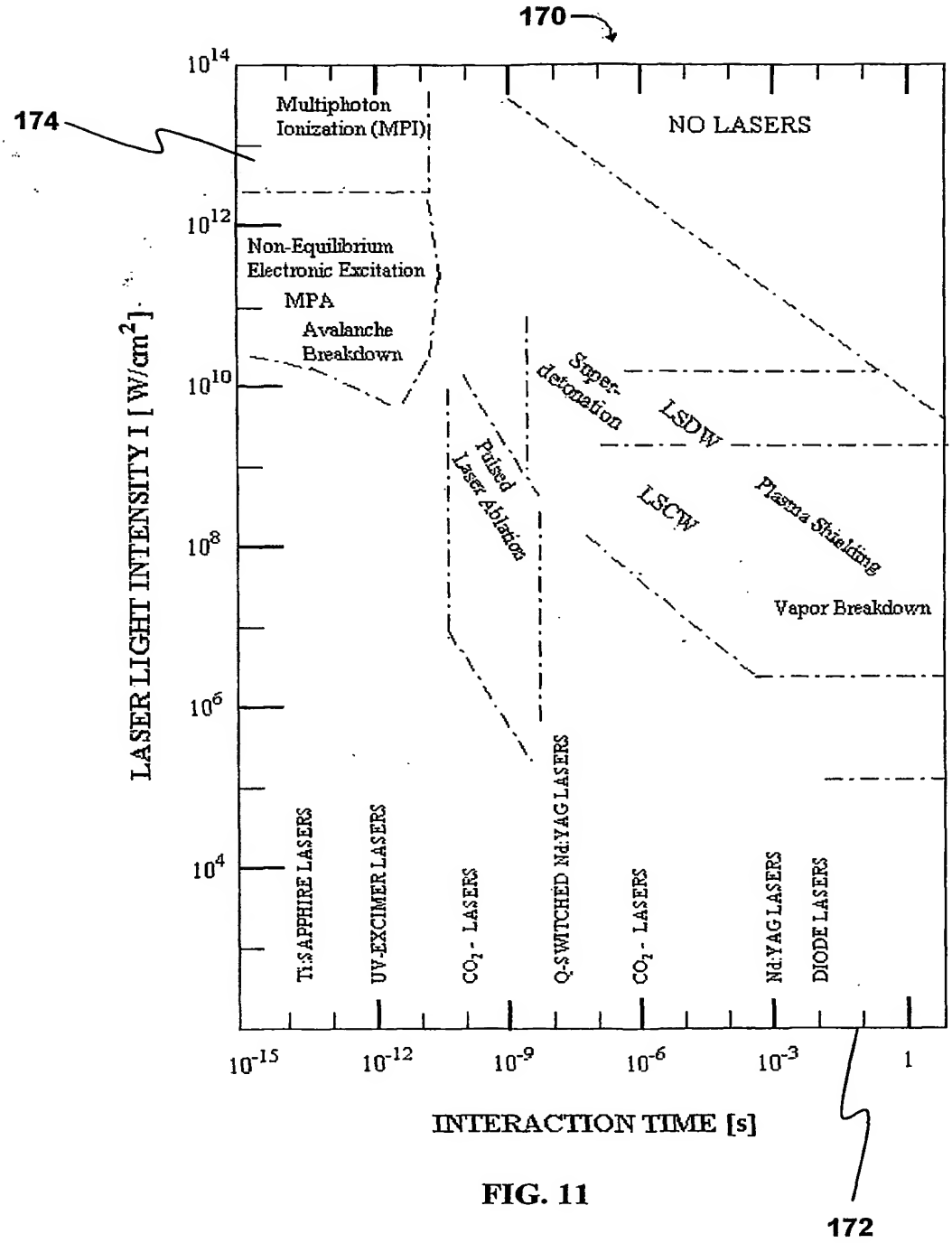
170
174
172
Multiphoton Ionization (MPI)
NO LASERS
Non-Equilibrium Electronic Excitation
MPA
Avalanche Breakdown
Super-detonation
LSDW
Pulsed Laser Ablation
LSCW
Plasma Shielding
Vapor Breakdown
LASER LIGHT INTENSITY I [W/cm^2]
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
Ti:SAPPHIRE LASERS
UV-EXCIMER LASERS
CO_2 - LASERS
Q-SWITCHED Nd:YAG LASERS
CO_2 - LASERS
Nd:YAG LASERS
DIODE LASERS
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
1
INTERACTION TIME [s]

FIG. 11

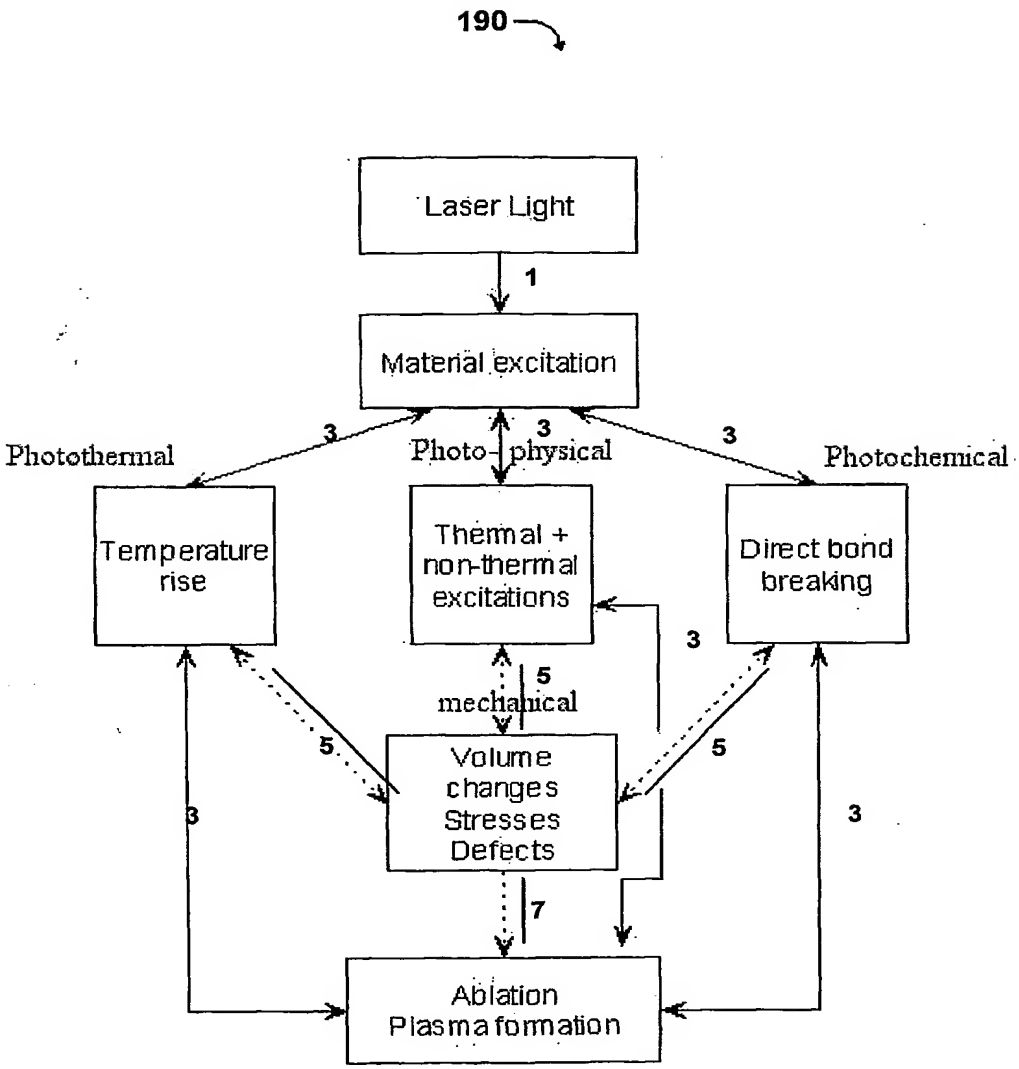
190
Laser Light
1
Material excitation
3
3
3
Photothermal
Photo-physical
Photochemical
Temperature rise
Thermal + non-thermal excitations
Direct bond breaking
3
5
mechanical
5
5
Volume changes Stresses Defects
3
3
7
Ablation Plasma formation

FIG. 12

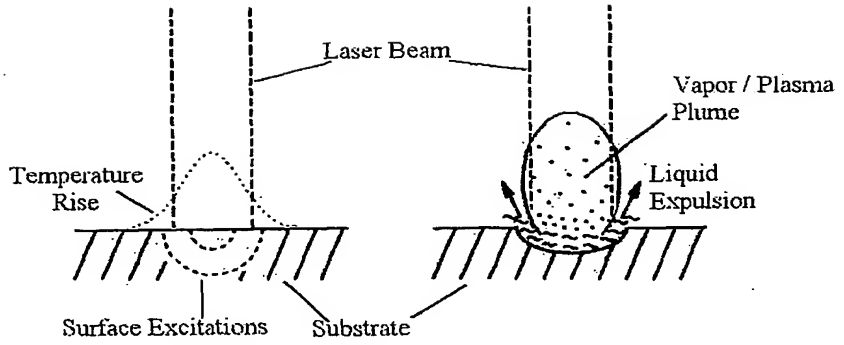
Laser Beam
Vapor / Plasma Plume
Temperature Rise
Liquid Expulsion
Surface Excitations
Substrate

FIG. 13

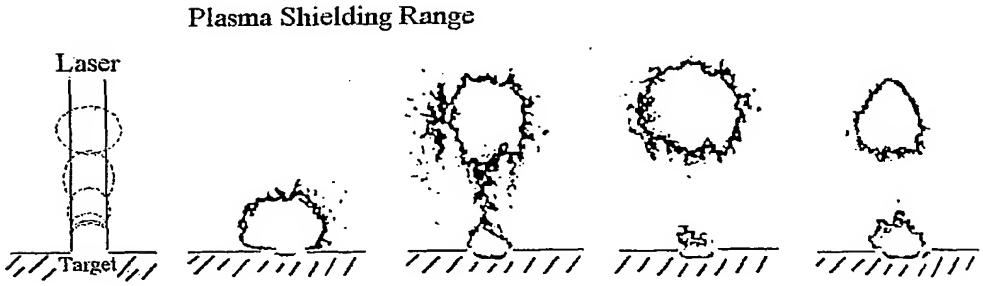
Plasma Shielding Range
Laser
Target

FIG. 14

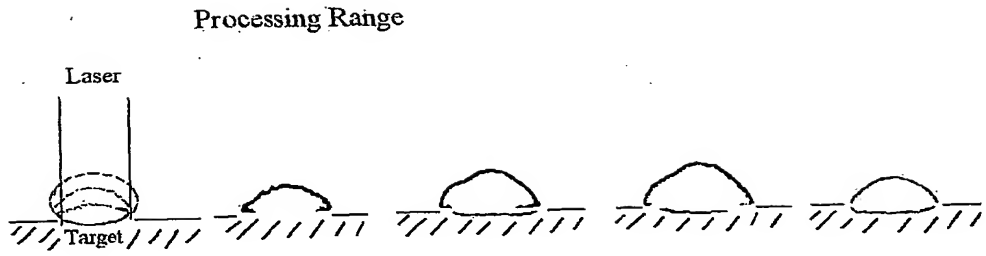

FIG. 15

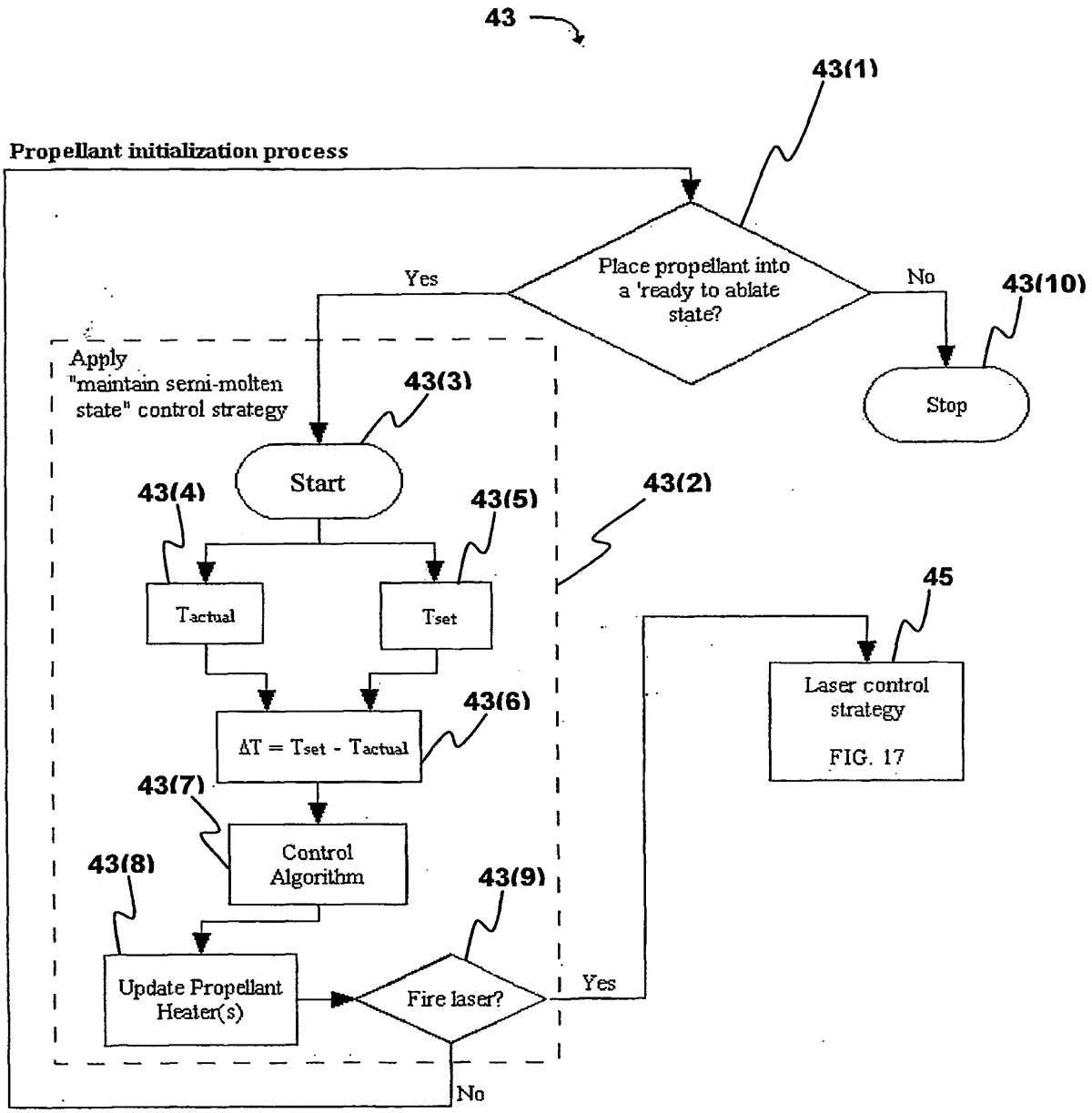
43
43(1)
Propellant initialization process
Place propellant into a 'ready to ablate state?
Yes
No
43(10)
Stop
Apply "maintain semi-molten state" control strategy
43(3)
Start
43(4)
43(5)
43(2)
Tactual
Tset
45
Laser control strategy
FIG. 17
43(6)
ΔT = Tset - Tactual
43(7)
Control Algorithm
43(8)
43(9)
Update Propellant Heater(s)
Fire laser?
Yes
No

FIG. 16

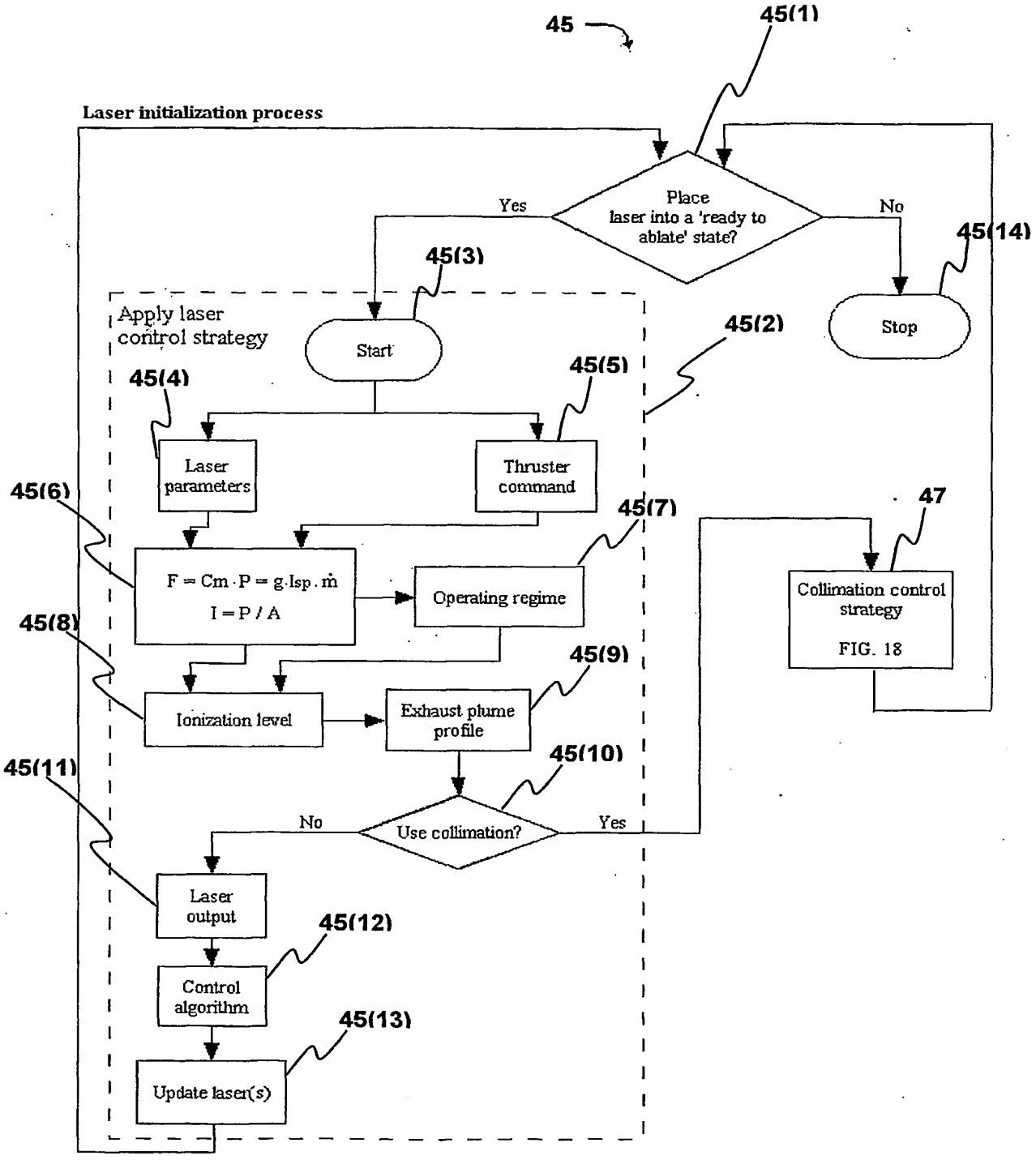
45
45(1)
Laser initialization process
Place laser into a 'ready to ablate' state?
Yes
No
45(14)
Stop
45(3)
Apply laser control strategy
Start
45(2)
45(4)
45(5)
Laser parameters
Thruster command
45(6)
45(7)
47
F = Cm · P = g · Isp · ṁ
I = P / A
Operating regime
Collimation control strategy
FIG. 18
45(8)
45(9)
Ionization level
Exhaust plume profile
45(10)
45(11)
No
Use collimation?
Yes
Laser output
45(12)
Control algorithm
45(13)
Update laser(s)

FIG. 17

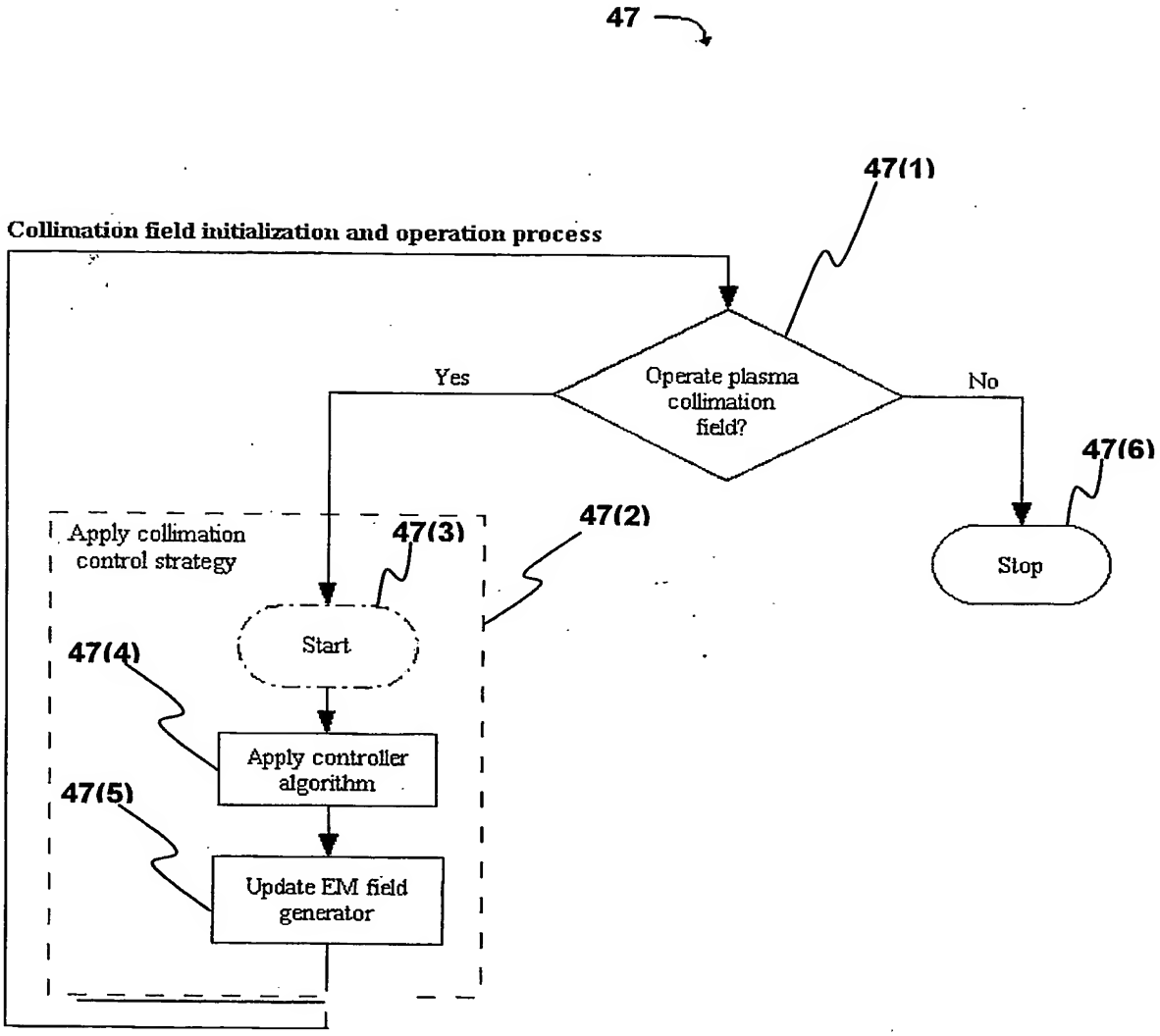
47
47(1)
Collimation field initialization and operation process
Operate plasma collimation field?
Yes
No
47(6)
Stop
47(2)
Apply collimation control strategy
47(3)
Start
47(4)
Apply controller algorithm
47(5)
Update EM field generator

FIG. 18

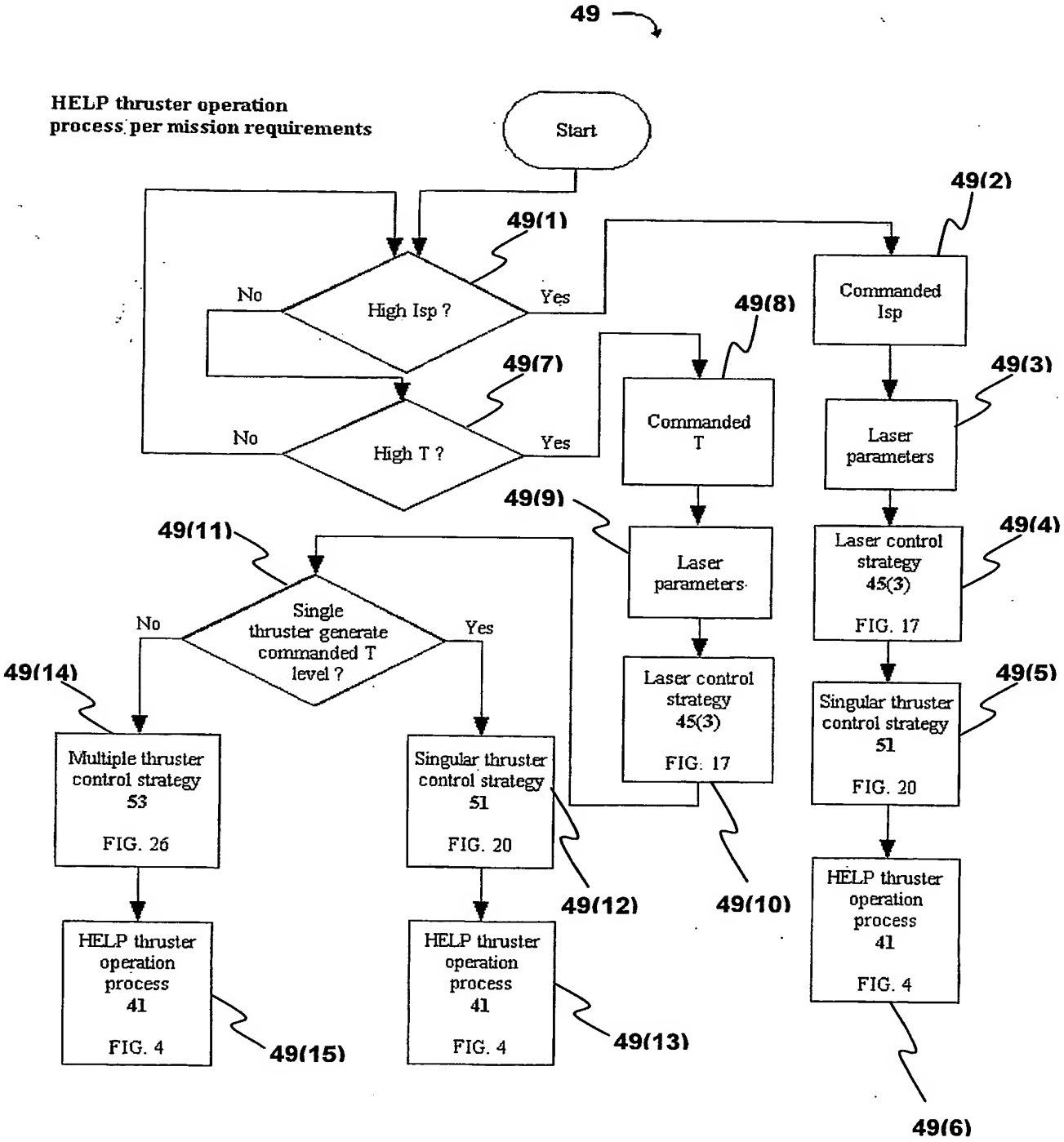
49
HELP thruster operation process per mission requirements
Start
49(1)
High Isp ?
No
Yes
49(2)
Commanded Isp
49(3)
Laser parameters
49(4)
Laser control strategy 45(3) FIG. 17
49(5)
Singular thruster control strategy 51 FIG. 20
49(6)
HELP thruster operation process 41 FIG. 4
49(7)
High T ?
No
Yes
49(8)
Commanded T
49(9)
Laser parameters
Laser control strategy 45(3) FIG. 17
49(10)
49(11)
Single thruster generate commanded T level ?
No
Yes
49(12)
Singular thruster control strategy 51 FIG. 20
HELP thruster operation process 41 FIG. 4
49(13)
49(14)
Multiple thruster control strategy 53 FIG. 26
HELP thruster operation process 41 FIG. 4
49(15)

FIG. 19

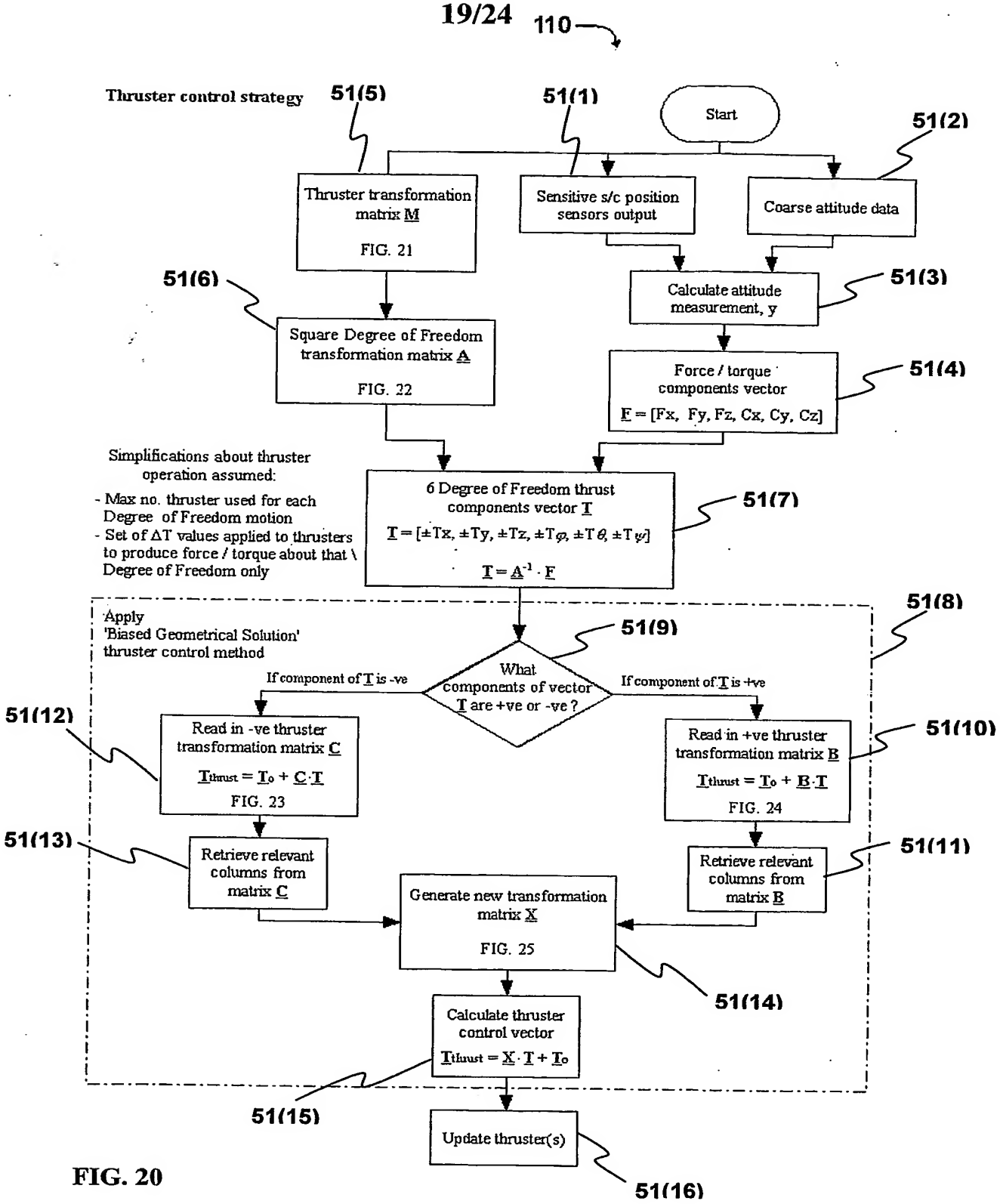
110
Thruster control strategy
51(5)
51(1)
Start
51(2)
Thruster transformation matrix M
FIG. 21
Sensitive s/c position sensors output
Coarse attitude data
51(6)
51(3)
Calculate attitude measurement, y
Square Degree of Freedom transformation matrix A
FIG. 22
Force / torque components vector
F = [Fx, Fy, Fz, Cx, Cy, Cz]
51(4)
Simplifications about thruster operation assumed:
- Max no. thruster used for each Degree of Freedom motion
- Set of ΔT values applied to thrusters to produce force / torque about that \ Degree of Freedom only
6 Degree of Freedom thrust components vector T
T = [±Tx, ±Ty, ±Tz, ±Tφ, ±Tθ, ±Tψ]
T = A-1 · F
51(7)
51(8)
Apply 'Biased Geometrical Solution' thruster control method
51(9)
What components of vector T are +ve or -ve ?
If component of T is -ve
If component of T is +ve
51(12)
Read in -ve thruster transformation matrix C
Tthrust = To + C·T
FIG. 23
Read in +ve thruster transformation matrix B
Tthrust = To + B·T
FIG. 24
51(10)
51(13)
Retrieve relevant columns from matrix C
Retrieve relevant columns from matrix B
51(11)
Generate new transformation matrix X
FIG. 25
51(14)
Calculate thruster control vector
Tthrust = X · T + To
51(15)
Update thruster(s)
51(16)

FIG. 20

$\underline{F} = \underline{M} * \underline{T}_{thrust}$

$\underline{F}$	$\underline{M}$												$\underline{T}_{thrust}$
F_x	cos70°	cos70°	cos70°	0	cos20°* cos30°	-cos20°* cos30°	-cos70°	-cos70°	-cos70°	0	-cos20°* cos30°	cos20°* cos30°	T_1
F_y	0	cos20°* cos30°	-cos20°* cos30°	-cos70°	-cos70°	-cos70°	0	-cos20°* cos30°	cos20°* cos30°	cos70°	cos70°	cos70°	T_2
F_z =	cos20°	-cos20°* cos60°	-cos20°* cos60°	cos20°	-cos20°* cos60°	-cos20°* cos60°	cos20°	-cos20°* cos60°	-cos20°* cos60°	cos20°	-cos20°* cos60°	-cos20°* cos60°	T_3
C_ϕ	0	0	0	-cos20°*D	-cos20°* cos60°*D	cos20°* cos60°*D	0	0	0	cos20°*D	-cos20°* cos60°*D	-cos20°* cos60°*D	T_4
C_θ	-cos20°D	cos20°* cos60°	cos20°* cos60°*D	0	0	0	cos20°*D	- cos20°* cos60°*D	-cos20°* cos60°*D	0	0	0	T_5
C_ψ	0	cos20°* cos30°*D	cos20°* cos30°*D	0	cos20°* cos30°*D	-cos20°* cos30°*D	0	cos20°* cos30°*D	-cos20°* cos30°*D	0	cos20°* cos30°*D	-cos20°* cos30°*D	T_6
													T_7
													T_8
													T_9
													T_{10}
													T_{11}
													T_{12}

Where

F = Force
C = Torque
T = Thrust

FIG. 21

F = **A** * **T**

F	A						T
Fx	(3cos70°+ 2cos20°*cos30°)	0	0	0	0	0	Tx
Fy	0	(3cos70°+ 2cos20°*cos30°)	0	0	0	0	Ty
Fz =	0	0	(4cos20°)	0	0	0	Tz
Cϕ	0	0	0	(2cos20°*D+ 2cos20°* cos60°*D)	0	0	Tϕ
Cθ	0	0	0	0	(2cos20°*D+ 2cos20°*cos60°*D)	0	Tθ
Cψ	0	0	0	0	0	(4cos20°* cos60°*D)	Tψ

FIG. 22

$\mathbf{T}_{thrust}$ = **C** * **T** + $\mathbf{T}_o$

T_{thrust}	C						T	Bias thrust T_o
	X	y	z	ϕ	θ	ψ		T_o
T1	0	0.5	0	0	2	1	-Tx	1
T2	0	0	1	0.5	0	0	-Ty	1
T3	0	1	1	0.5	0	1	-Tz	1
T4	0.5	1	0	2	0	0	-Tϕ	1
T5	0	1	1	0	0.5	0	-Tθ	1
T6 =	1	1	1	0	0.5	1	-Tψ	+ 1
T7	1	0.5	0	0	0	1		1
T8	1	1	1	0.5	1	0		1
T9	1	0	1	0.5	1	1		1
T10	0.5	0	0	0	0	0		1
T11	1	0	1	1	0.5	0		1
T12	0	0	1	1	0.5	1		1

FIG. 23

$\underline{T}_{thrust} = \underline{B} * \underline{T} + \underline{T}_o$

$\underline{T}_{thrust}$	$\underline{B}$						$\underline{T}$	Bias thrust $\underline{T}_o$
	x	y	z	ϕ	θ	ψ		T_o
T_1	1	0.5	1	0	0	1	T_x	1
T_2	1	1	0	0.5	1	1	T_y	1
T_3	1	0	0	0.5	1	0	T_z	1
T_4	0.5	0	1	0	0	0	T_ϕ	1
T_5	1	0	0	1	0.5	1	T_θ	1
T_6 =	0	0	0	0.5	0.5	0	T_ψ	+ 1
T_7	0	0.5	1	0	2	1		1
T_8	0	0	0	0.5	0	1		1
T_9	0	1	0	0.5	0	0		1
T_{10}	0.5	1	1	2	0	0		1
T_{11}	0	1	0	0	0.5	1		1
T_{12}	1	1	0	0	0.5	0		1

FIG. 24

$\underline{T}_{thrust} = \underline{X} * \underline{T} + \underline{T}_o$

$\underline{T}_{thrust}$	$\underline{X}$						$\underline{T}$	Bias thrust $\underline{T}_o$
	x	y	z	ϕ	θ	ψ		T_o
T_1	0	0	0	0	0	0	$-T_x$	1
T_2	0	0	0	0	0	0	$-T_y$	1
T_3	0	0	0	0	0	0	$-T_z$	1
T_4	0.5	0	0	0	0	0	$-T_\phi$	1
T_5	0	0	0	0	0	0	$-T_\theta$	1
T_6 =	1	0	0	0	0	0	$-T_\psi$	+ 1
T_7	1	0	0	0	0	0		1
T_8	1	0	0	0	0	0		1
T_9	1	0	0	0	0	0		1
T_{10}	0.5	0	0	0	0	0		1
T_{11}	1	0	0	0	0	0		1
T_{12}	0	0	0	0	0	0		1

FIG. 25

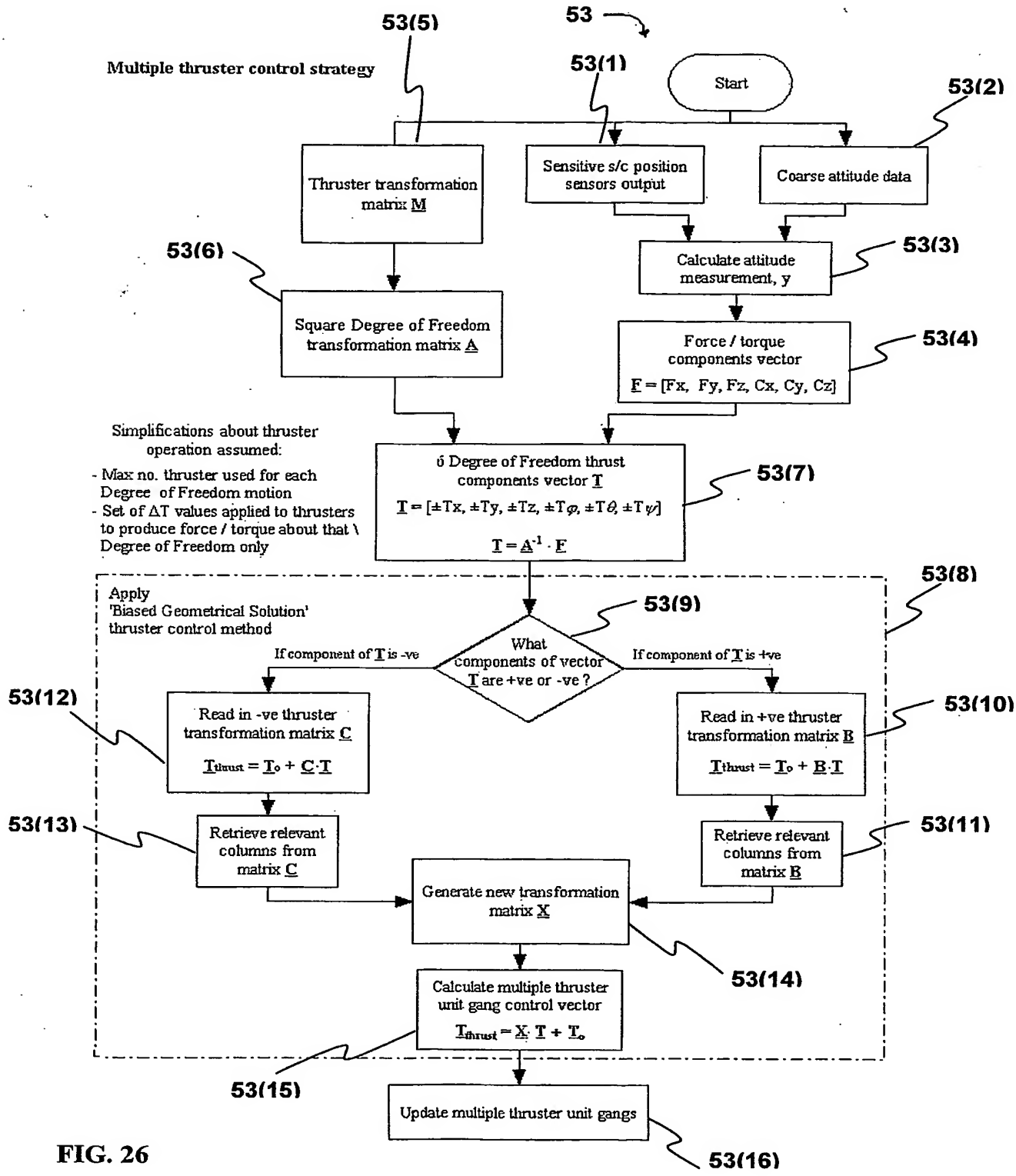
Multiple thruster control strategy
53
53(1)
53(2)
53(3)
53(4)
53(5)
53(6)
53(7)
53(8)
53(9)
53(10)
53(11)
53(12)
53(13)
53(14)
53(15)
53(16)
Start
Thruster transformation matrix M
Sensitive s/c position sensors output
Coarse attitude data
Calculate attitude measurement, y
Square Degree of Freedom transformation matrix A
Force / torque components vector
F = [Fx, Fy, Fz, Cx, Cy, Cz]
Simplifications about thruster operation assumed:
- Max no. thruster used for each Degree of Freedom motion
- Set of ΔT values applied to thrusters to produce force / torque about that \ Degree of Freedom only
ó Degree of Freedom thrust components vector T
T = [±Tx, ±Ty, ±Tz, ±Tφ, ±Tθ, ±Tψ]
T = A-1 · F
Apply 'Biased Geometrical Solution' thruster control method
What components of vector T are +ve or -ve ?
If component of T is -ve
If component of T is +ve
Read in -ve thruster transformation matrix C
Tthrust = To + C·T
Read in +ve thruster transformation matrix B
Tthrust = To + B·T
Retrieve relevant columns from matrix C
Retrieve relevant columns from matrix B
Generate new transformation matrix X
Calculate multiple thruster unit gang control vector
Tthrust = X· T + To
Update multiple thruster unit gangs

FIG. 26

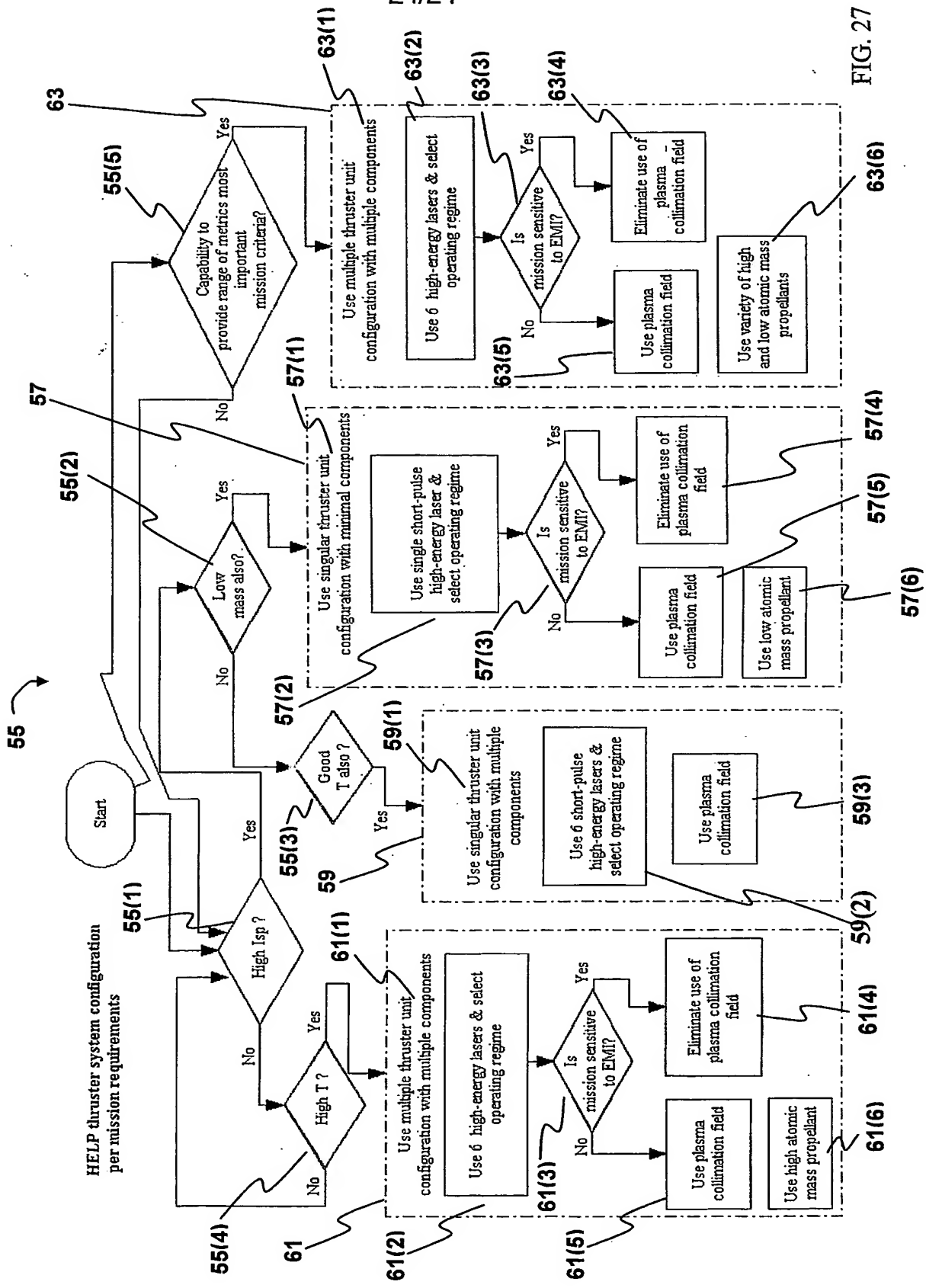
HELP thruster system configuration per mission requirements
55
Start
55(1)
High Isp ?
Yes
No
55(2)
Low mass also?
Yes
No
55(3)
Good T also ?
Yes
59
55(4)
High T ?
Yes
No
55(5)
Capability to provide range of metrics most important mission criteria?
Yes
No
57
57(1)
Use singular thruster unit configuration with minimal components
57(2)
Use single short-pulse high-energy laser & select operating regime
57(3)
Is mission sensitive to EMI?
Yes
No
57(4)
Eliminate use of plasma collimation field
57(5)
Use plasma collimation field
57(6)
Use low atomic mass propellant
59(1)
Use singular thruster unit configuration with multiple components
59(2)
Use 6 short-pulse high-energy lasers & select operating regime
59(3)
Use plasma collimation field
61
61(1)
Use multiple thruster unit configuration with multiple components
61(2)
Use 6 high-energy lasers & select operating regime
61(3)
Is mission sensitive to EMI?
Yes
No
61(4)
Eliminate use of plasma collimation field
61(5)
Use plasma collimation field
61(6)
Use high atomic mass propellant
63
63(1)
Use multiple thruster unit configuration with multiple components
63(2)
Use 6 high-energy lasers & select operating regime
63(3)
Is mission sensitive to EMI?
Yes
No
63(4)
Eliminate use of plasma collimation field
63(5)
Use plasma collimation field
63(6)
Use variety of high and low atomic mass propellants

FIG. 27